Ph.D Synopsis

"Timing analysis of emission from compact objects."

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Abstract of the proposed work plan:

Aim of the proposed research work is to study the timing analysis of emission from compact objects like neutron stars, black holes, supernovae or GRBs in host galaxy. Till the date, time-domain determination of compact object's type remains an untapped tool (Astro2020 Science White Paper). This study can be done by using data from AstroSat mission and/or other space missions like XMM-Newton, Chandra X-Ray Telescope, Swift etc having upgraded sensitivity, high energy resolution, capability for monitoring highly variable compact objects.

I am planning to construct a critically selected sample of X-ray compact sources on the basis of their X-ray emission properties. This study will mostly focus on their spectral and timing properties. Study of the discrete X-ray compact sources (like Neutron star, Black hole, supernovae or GRBs) will facilitate a better understanding of the various physical processes involved which powers these objects, their spectral and temporal variability and the state of matter very close to the central source where General theory of relativity (GTR) is applicable.

Introduction:

Compact object

The Compact Objects group studies the astrophysics of neutron stars and black holes, using them as unique cosmic laboratories for to know more about the physics of extremely high gravitational and electromagnetic fields and of matter at extreme densities**.** The study of the compact object as stellar remnant is an important area of research in modern astrophysics. We have so far acquired an ample information regarding evolutionary phases of stellar objects, however, are yet to decode the nature of the stars after their death. What happens when a star dies? What are the remaining objects when a star dies? What is the state of matter at these extremely high densities? How these cosmic laboratories help us to know more about the physics behind it? These are some of the questions that need to be answered by using the present day knowledge of these compact objects.

From the previous studies, we know that after the death of a star, it gets converted into either one of the following objects through events like supernova explosion;

1. White Dwarf
2. Neutron star/Pulsar
3. Black hole

1. *White Dwarf:*

It is also called as degenerate dwarf. This stellar remnant is composed of electron degenerate matter. It contains a huge amount of mass in a tiny fraction of space hence we called it as one of the compact objects. For the sake of our convenience if the whole mass of the sun is compressed in the size of the earth, this how the density of the white dwarf is. White dwarfs are the faint luminous objects. This faint luminosity is due to the thermal energy created inside due to very high density of matter. These objects are formed when a normal mass star like our sun , when it's nuclear fuels comes to an end and it's core is incapable to maintain the radiation pressure to separate outer envelope of the star at this time star dies in planetary nebula in which the core left behind intact and outer envelope get thrown away in outer space . The final remnant is called as White dwarf. There is a famous relation behind the formation of these white dwarfs is the physics of degeneracy yields a maximum mass for non-rotating, while dwarfs follows the Chandrashekhar mass limit which is approximately 1.44 times mass that of the sun. Beyond which the star can not sustain electron degeneracy pressure and it may hence converted into a neutron star or black hole.

2. *Neutron star:*

Neutron star is the collapsed core of a giant star having mass ranges in between 10 to 30 solar masses and supernova remnant of one of these massive stars. Neutron stars are generally formed in type II supernovae. Size of the neutron star is even lesser than white dwarf i.e its radius is about several 10 kilometers[1], hence having more density than that of white dwarfs. Most of the model suggests that neutron star is composed of mostly neutrons. These objects can sustain their sizes due electron degeneracy pressure created by the matter composed of it, due to this it will not collapse further . Reason behind the degeneracy pressure created by the neutrons is Pauli's Exclusion principle. [2]If the remnant star has a mass exceeding the Tolman–Oppenheimer–Volkoff limit, it continues collapsing to form a black hole. It has been observed that neutron star has a temperature near about 600000 K. These objects are so dense that even a match box weight of neutron star matter is approximately 3 billion metric tons [3]. It is thought that the number of neutron star that contain in the milky-way galaxy is near about 100 billions. This number is obtained by seeing the number of stars undergoes a supernova explosion in the galaxy [4]. The merger of binary neutron stars may be the source of short-duration gamma-ray bursts and are likely strong sources of gravitational waves. In 2017, a direct detection (GW170817) of the gravitational waves from such an event was made, and gravitational waves have also been indirectly detected in a system where two neutron stars orbit each other .

From all known neutron stars Near about 5% of them are the members of a binary system. Binary systems containing neutron stars often emit X-rays, which are emitted by hot gas as it falls towards the surface of the neutron star. The source of the gas is the companion star, the outer layers of which can be stripped off by the gravitational force of the neutron star if the two stars are sufficiently close. As the neutron star accretes this gas its mass can increase; if enough mass is accreted the neutron star may collapse into a black hole[5]. In binary ultimately the neutron stars will come into contact and coalesce. The coalescence of binary neutron stars is one of the leading models for the origin of short

gamma-ray bursts. The light emitted in the kilonova is believed to come from the radioactive decay of material ejected in the merger of the two neutron stars. This material may be responsible for the production of many of the chemical elements beyond iron, as opposed to the supernova nucleosynthesis theory.

3. *Black Hole:*

The name 'Black hole' itself suggests that something invisible there. We won't be able to see any electromagnetic waves come out of it, hence the name Black hole. This is one of the most famous and mysterious objects in the universe. If we are talking about science part of it then black holes are the object in the universe which are having such immense gravity that not only particles but electromagnetic waves also can't escape out of its gravity. As this gravity in accordance with the general theory of relativity that compact mass can deform spacetime. The boundary surrounding the black hole beyond which no one can escape out is called "event horizon".

Abstract:

Physics In the vicinity of these compact objects is much different and need to verify the unusual phenomenon like High energy, X-Ray and Gamma Radiation, High frequency oscillation, Relativistic jets etc. compact objects are having many mysterious things at their own like density of neutron star is much more than nuclear density. In addition to that they are able to produce huge magnetic field which can not be produced on the earth by means of any existing practical instruments. In Comparison to the white dwarfs, neutron stars and black holes are extremely dense objects. If we see the black hole classically then its density goes to infinity inside the singularity. In the vicinity of black hole gravitational effect plays a major role which is outcome of general theory of relativity. We can study these various aspects of it by time domain emission analysis from these objects in X-Ray band using various space based telescopes.

Objective of your research:

With reference to the above mentioned title I would like to analyse various aspects of timing analysis of emission from compact objects like nature of the objects, their Orbital periods, spectral variation,Nucleosynthesis in GRBs, Radiation polarisation:
Percentage change in the detection of polarisation (Astrosat is more useful for this kind of research), of these compact objects in the emission. QPO's(Quasi-periodic Oscillations[6] Many questions about the phenomenon of QPOs remain unanswered, it is believed that they occur when X-rays are emitted near the inner edge of an accretion disk in which gas swirls onto a compact object, for instance, a neutron star or a black hole. Astronomers hope that these oscillations could advance our knowledge of the innermost regions of accretion disks.X-ray binaries consist of a normal star or a white dwarf transferring mass onto a neutron star or a black hole. Based on the mass of the companion star, astronomers divide them into low mass X-ray binaries (LMXB) and high-mass X-ray binaries (HMXB). When X-ray light from these objects flickers about certain frequencies, such behavior is known as quasi-periodic oscillations (QPOs). Origin of gravitational wave

sources and along with it how can we improve the event detection rate by using the ground based detectors like LIGO.

Instrumentation:

Telescopes that can be used to study the above mentioned phenomenon are as follows;

1. *AstroSAT(specifically CZTI):*
   On board ASTROSAT are five astronomy payloads for simultaneous multi-band observations: Twin 38-cm Ultraviolet Imaging telescope **(UVIT)** covering Far-UV to optical bands. Three units of Large Area Xenon Proportional Counters **(LAXPC)** covering medium energy X-rays from 3 to 80 keV with an effective area of 8000 sq.cm. at 10 keV. A Soft X-ray Telescope **(SXT)** with conical foil mirrors and X-ray CCD detector, covering the energy range 0.3-8 keV. The effective area will be about 120 sq.cm. at 1 keV. A Cadmium-Zinc-Telluride coded-mask imager **(CZTI)**, covering hard X-rays from 10 to 150 keV, with about 6 deg field of view and 480 sq.cm. effective area. A Scanning Sky Monitor **(SSM)** consisting of three one-dimensional position-sensitive proportional counters with coded masks. The assembly is placed on a rotating platform to scan the available sky once every six hours in order to locate transient X-ray sources.
2. *Swift:*
   Swift Gamma-ray burst mission with wide-field hard X-ray detector (BAT), X-ray telescopes with CCD detectors (XRT), and optical/UV telescope (UVOT). While primarily chasing GRBs, Swift is also observing other sources as time is available. The X-ray telescope has a resolution similar to that of XMM-Newton. The CCD is similar to the EPIC-MOS. The UVOT is a copy of the Optical Monitor on XMM-Newton. The wide-field detector is producing an all-sky survey in hard X-rays (> 10 keV).
3. *Chandra X-Ray Telescope:*
   Chandra boasts the best (and most expensive) telescope ever built, giving a sub-arcsecond resolution. Imaging is provided by CCD and microchannel plate imagers. High resolution spectroscopy by two gratings that can be placed in the optical path behind the mirrors.
   Chandra is best for...
   - Anything requiring better than 5 arcseconds spatial resolution.
   - High resolution spectroscopy for energies < 0.5 or > 2 keV.

4. *XMM-Newton:*
   Three X-ray telescopes and one optical/UV telescope giving large effective area and simultaneous observations.
   - *EPIC* - two MOS and one PN CCD spectrometers with 7 and 2 chips respectively. PN has better efficiency at high energies.
   - *RGS* - two grating dispersing spectrum onto 8 MOS chips. Each RGS intercepts 50% of the X-rays passing through its telescope.

- *OM* - 30cm optical/UV telescope with filter set and two grisms. Generally underused. Limiting sensitivity B=24.
- XMM-Newton has 3 mirrors, 2 of which have reflection gratings, providing simultaneous high resolution spectroscopy and imaging. There is also an optical monitor telescope.

XMM-Newton is best for...

- Imaging or imaging-spectroscopy which does not require a resolution of 5 arcseconds or better.

-High resolution spectroscopy for energies 0.5 < E < 2 keV.

- High resolution spectroscopy on extended objects that are larger than 10 arcseconds and smaller than 1 arcminute.

Methodology to be adopted:

The proposed study on investigating spectral and timing properties of compact objects in the host galaxy, plans to follow the following methodology:

a) *Sample selection:*

A sample of compact objects will be selected by applying selection criteria depending on the availability of the good quality data in the wide X-ray band in host galaxy with AstroSat mission or equivalent space telescope.

b) *Observations:*

For the study of emission from compact objects, we expect to get fresh data by submitting our own proposals or available in the archive of the proposed Indian Space Mission AstroSat using X-ray LAXPC, SXT and CZTI detectors. We have preliminarily searched for the availability of X-ray data in the HEASARC archive for different X-ray observatories and have satisfied our self about the availability of the data. We will also include the results based on XMM-Newton, Chandra X-ray, and Swift data whenever Needed.The Large Area X-ray Proportional Counter (LAXPC), designed and developed at TIFR, Mumbai, is one of the major payloads on ASTROSAT. LAXPC will provide the largest effective area among all satellite missions flown so far, worldwide, and will remain so for the next 10 years, for X-ray studies in the 3-80 keV energy range.

c) *Data Analysis:*

1. *X-ray data:*

X-ray detectors are photon-counting in contrast to those in most other wavebands which measure incoming flux. In consequence, basic X-ray data usually comprise lists of events and their attributes. X-ray datasets are usually photon-limited, particularly for newer missions such as Chandra and XMM-Newton. Images, spectra, and lightcurves created from the event lists may well have a few or even no photons in many bins. The data analysis techniques (and statistics) developed in other wavebands may not transfer to X-ray astronomy. The basic data file usually comprises time-tagged events, each with a position (in detector and sky coordinates) and an energy (often called channel, PHA or PI for historical reasons). Thus each event can be thought of as occupying a position in a 4-D space. The event may have other attributes of interest - eg. for the CCDs

pattern of pixels from which the charge for this event was accumulated. It is often possible to increase S/N by selecting on these secondary attributes. After filtering the events as required we project them onto 1-D or 2-D subspaces and bin them up to give images, energy spectra, or lightcurves (time series).
Each of these binned datasets requires its own calibration products.

• Image analysis uses :
  - exposure maps - the mirror and detector sensitivity across the field-of-view (taking into account any changes in aspect ie pointing direction).
  - point spread function (PSF) - the probability that a photon of given energy and position is registered in a given image pixel.

• Energy spectral analysis uses :
  - response matrices - the probability that a photon of given energy is registered in a given channel.

The most important thing about the X-Ray data analysis is the data 'Calibration'.There is always a systematic error term associated with your data analysis. If you have the misfortune to have very high S/N then this systematic term may dominate.
The AstroSat LAXPC (Large Area X-ray Proportional Counter) X-ray wide band 3.0-80.0 keV and SXT (Soft X-ray Telescope) 0.3-8.0 keV data on the target X-ray source acquired from the archive of AstroSat Observatory. It will be reduced and analyzed in a uniform, self-consistent manner by using our own prepared codes or scripted analysis pipeline or softwares proposed and developed by AstroSat mission. For the spectral and timing analysis of RXTE, XMM-Newton and chandra-xray data,latest HEASOFT XSPEC (Strickland et al. 2002) or ISIS and XRONS software package will be used . The instrumental calibration (to update the instrumental gain and astrometry solution) can be performed using the latest Calibration Database (CALDB) of related mission.

2. X-ray Spectral Analysis:

For an observed X-ray source, a spectrum of the X-ray photons in different energy bands and for different bin sizes will be extracted using the AstroSat X-ray data analysis software routine or pipelines. This routine calculates a weighted redistribution matrix file (RMF) and ancillary response file (ARF) appropriate for extended sources spread over the X-ray detectors of AstroSat mission. Finally, using package XSPEC or ISIS these extracted spectra of X-ray source will be fitted to the different models. These models are available in the library of XSPEC and ISIS, however, for this class of targets Bremsstrahlung or power law, compTT, nth comp. (continuum model) model and xillver family, reflionx models (that covers narrow and broad emission and absorption features, broadened Fe line emission and reflection features) in conjunction with the wabs, tbabs, xstar (photoelectric absorption model) will be appropriate. Broad band Spectral analysis for 0.3-100 keV energy range study the spectral variations for different parameters.

3. *X-ray Timing Analysis:*

_____ We will obtain the light curves on a wide variety of time scales and energy ranges and analyse them to extract and study fractional rms variations, colour-colour and hardness intensity diagram in compact X-ray binaries. We will also perform the power spectral analysis and cross spectra analysis.Here, we will also focus on investigating the energy dependence of the rapid aperiodic variability and the complex phase lag behavior of the 0.5 - 10 Hz QPOs. In this study, we have put special emphasis on the energy dependence of the broadband variability seen in the observed sources.

Importance of study:

Importance of time domain study of compact objects is because these objects are showing mysterious effect during its formation period and in his whole life. Many of the things we don't know much detail about objects like black holes and neutron stars. As various national and international research institutes are involving their man power to understand the physics behind these objects, which will also enhance the technology and science at times. Eminent people are working on the science case behind the experiments going to happen in these cosmic laboratories like black holes and neutron stars. And trying to find out many unresolved questions in the context of timing analysis of the compact objects.

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